Window Query Processing in Highly Dynamic GeoSensor Networks: Issues and Solutions

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ABSTRACT

Wireless sensor networks have recently received a lot of attention due to a wide range of applications such as object tracking, environmental monitoring, warehouse inventory, and health care [15, 29]. In these applications, physical data is continuously collected by the sensor nodes in order to facilitate application specific processing and analysis. A database-style query interface is natural for development of applications and systems on sensor networks. There are projects pursuing this research direction [13, 14, 25]. However, these existing works have not yet explored the *spatial* property and the *dynamic* characteristics of sensor networks.

In this paper, we investigate how to process a *window query* in *highly dynamic GeoSensor networks* and propose several innovative ideas on enabling techniques. The networks considered are highly dynamic because the sensor nodes can move around (by self-propelling or attaching themselves to moving objects) as well as turn to sleeping mode. There exist many research issues in executing a window query in such sensor networks. The dynamic characteristics make those issues non-trivial. A critical set of networking protocols and access methods need to be developed. In this paper, we present a location-based stateless protocol for routing a window query to its targeted area, a space-dividing algorithm for query propagation and data aggregation in the queried area, and a solution to address the user mobility issue when the query result is returned.

1. INTRODUCTION

The availability of low-power micro-sensors, actuators, embedded processors, and RF radios has enabled distributed wireless sensing, collecting, processing, and dissemination of complex environmental data in many civil and military applications. In these applications, queries are often inserted into a network to extract and derive information from sensor nodes. There are a lot of research efforts aiming at building sensor network based systems to leverage the sensed data to applications. However, most of the existing works are based on design and requirements of some specialized application. Thus, they cannot be easily extended for other

applications. To facilitate rapid development of systems and applications on top of sensor networks, building blocks, programming models and service infrastructures are necessary to bridge the gap between underlying sensor networks and upper layer systems and applications.

A database style query interface is natural for development of applications and systems on sensor networks. The declarative, ad hoc query languages used in traditional database systems can be used to formulate queries to exploit various functionality of sensor nodes and retrieve data from the physical world. In deed, database technology, after many years of development, has matured and contributed significantly to the rapid growth of business and industry. Commercial, research, and open-source development tools are available to facilitate rapid implementations of applications and systems on databases. Thus, a query layer on top of the sensor networks will allow database developers to leverage their experience and knowledge and to use existing tools and methodologies for designs and implementations of sensor network based systems and applications.

Sensor databases such as Cougar [25] and TinyDB [13, 14] have been proposed. However, these existing works have not yet exploited the *spatial* property and the *dynamic* characteristics of sensor networks. In this paper, we investigate how to process a spatial *window query* in *highly dynamic sensor networks* (HDSN) and present several innovative ideas on enabling techniques for query processing. The network is highly dynamic because sensor nodes may go to *sleeping* mode to save energy as well as move around by self-propelling or attaching themselves to moving objects (e.g. vehicles, air, water). In addition to the capacities static sensor nodes typically possess (e.g. computation, storage, communication and sensing ability), here we assume that sensor nodes are location-aware via GPS or other positioning techniques [6, 17]. The spatial property of sensor nodes is important since sensor networks are deployed and operated in a geographical area after all. We are particularly interested in window query because it is one of the most fundamental and important queries supported in spatial databases. A window query on sensor database retrieves the physical data falling within specified *query window*, a 2- to 3-dimensional area of interest specified by its user.

There are obviously many new challenges for processing spatial window queries in HDSNs. In this paper, we use the following query execution plan as a vehicle to examine various research issues:

1. Routing the query towards an area specified by the query window;
2. Propagating the query within the query window;
3. Collecting and aggregating the data sensed in the query window;
4. Returning query result back to the query user (who is *mobile*).

Many technical problems need to be answered in order to carry out this plan. For example, how to route the query to the targeted area by taking energy, bandwidth, and latency into account; how to ensure a query reaches all the sensors located within window; how to collect and aggregate data without relying on a static or fixed agent; and how to deal with user mobility. To realize this execution plan, a critical set of networking protocols and access methods need to be developed. Although there is some work investigating either the window query processing or HDSNs, none provides a complete solution for window query processing in a HDSN. We have proposed innovative ideas and enabling solutions. Our proposals prevail for window query processing in HDSNs in the following aspects:

- Sensor nodes are able to make wise query routing decisions without state information of other nodes or the network. The proposed stateless protocol, namely, *spatial query routing* (SQR) enables efficient query routing in HDSNs where the topology frequent changes. Instead of serialized forwarding, pipelining techniques are employed in the protocol to reduce the delay of forwarder selection.
- Queries are propagated inside the query window in an energy-efficient way. The propagation is ensured to cover the whole query window.
- Query results are aggregated in a certain geographical region instead of at some pre-defined sensor node, which adopts well to the dynamics of HDSNs. Query results are processed and aggregated inside the query window, thus the number of transmissions is reduced.
- User mobility is accommodated by utilizing the static property of geographical region as well. The query result is delivered back to the mobile user, even if she moves during query processing.

The rest of this paper is organized as follows. Section 2 presents the backgrounds and the assumptions for our work and discusses various performance requirements. In Section 3, research challenges arising in the context of this study are investigated. Section 4 describes our main designs including spatial query routing algorithm, spatial propagation and aggregation techniques and a strategy for returning the query results back to mobile users. Related work is reviewed and compared with our proposals in Section 5. Finally, Section 6 concludes this paper and depicts future research directions.

2. PRELIMINARIES

In this section, we provide some backgrounds and discuss challenges faced in processing window queries in HDSNs. We first describe the assumptions we use as a basis, followed by a review of HDSNs and window

query. At the end, we give a list of performance metrics that need to be considered for evaluating query processing in sensor networks.

2.1 Assumptions

We assume that the sensor network is a pull-based, on-demand network. In other words, the network only provides data of interest upon users' requests. While the types of events and sensed data (e.g. temperature, pressure or humidity) are pre-defined and accessible from the sensor nodes, no sensing or transmission actions are taken by the nodes until the query is inserted into the network. This assumption is based on the fact that most of the sensor networks stay in low power mode in order to conserve energy and prolong the network lifetime. Nevertheless, a push-based network can be emulated by executing a long-running query in an on-demand network. We further assume that users are able to insert their queries from any sensor node, instead of through one or more stationary access points in the sensor networks. Finally, a user, who moves at will, is able to receive the query result back at different locations of the network.

2.2 Highly Dynamic Sensor Networks

Here we characterize the highly dynamic sensor networks (HDSNs). Generally speaking, the sensor nodes in HDSNs have the same functionalities of sensing, computation, communication and storage as the static sensor nodes commonly considered in the literature [1, 7]. Nevertheless, HDSNs also have the following important properties:

- Node Mobility: The sensor nodes in HDSNs are mobile. They may drive themselves by self-propelling (via wheels, micro-rockets, or other means) or by attaching themselves to certain transporters such as water, wind, vehicles and people. With self-propelling sensor nodes, a HDSN is self-adjustable to achieve better area coverage, load balances, lifetime, and other system functionalities. These intelligent sensor nodes can be controlled by the network administrator and adaptable to the queries or commands from the applications. On the other hand, for the sensor nodes attaching to transporters, their moving patterns are dependent on the transporters. The applications may have little control or influence on their movement.
- Energy Conservation: Sensor nodes may switch between *sleeping* mode and *active* mode in order to conserve energy and extend the lifetime of networks. Thus, a sensor node is not always accessible. From the viewpoint of the network, the sensor node joins and leaves the network periodically or asynchronously based on sleeping schedules derived from various factors such as node density, network size, bandwidth contention, etc.

- Unreliable Links and Node Failures: Another factor that contributes to the dynamics of networks is node and communication failures. This has a different impact from energy conservation because the available sensor nodes within the network will continue to decrease.

Sensor nodes with some or all of the above properties form a dynamic sensor network. While nodes sleep, node failure and unreliable communication exist in most sensor networks, here we stress the high mobility of sensor nodes. We argue that the mobility of sensor nodes is essential in a wider range of applications. For example, a sensor network for air pollution test, where all sensors are scattered in the air and transported by the wind; and a vehicle network, where sensor nodes are carried by moving vehicles. Applications are able to collect the data from the sensors about air pollution and traffic conditions. In addition, HDSNs may provide application layer solutions to some existing issues in the network layer. Take network topology adaptivity as an example: when an application observes that the density or the number of sensor nodes in Region X is not sufficient to satisfy the application requirements, it could command the redundant or idle sensor nodes in Region Y to move to Region X.

2.3 Location Awareness

In the context of this paper, we assume that the sensor nodes are location-aware via GPS and other positioning techniques. The location awareness of sensor nodes is very important since sensor networks are deployed and operated in a geographical area after all. Since the sensor nodes in HDSNs are mobile, location information is crucial not only for certain kinds of spatial queries but also for the sensor readings to be meaningful. In addition to the time, sensor ID and readings, location information is frequently used in query predicates and requested by the applications. Moreover, location is frequently used in routing, dissemination and location-based queries [3, 8, 10, 21, 20, 27, 28].

A location needs to be specified explicitly or implicitly for its use. Location models depend heavily on the underlying location identification techniques employed in the system and can be categorized as follows:

- **Geometric Model:** A location is specified as an n-dimensional coordinate (typically $n = 2$ or 3), e.g., the latitude/longitude pair in the *GPS*. The main advantage of this model is its compatibility across heterogeneous systems. However, providing such fine-grained location information may involve considerable cost and complexity.
- **Symbolic Model:** The location space is divided into disjointed zones, each of which is identified by a unique name. Examples are Cricket [18] and the cellular infrastructure. The symbolic model is

in general cheaper to deploy than the geometric model because of the lower cost of the coarser location granularity. Also, being discrete and well-structured, location information based on the symbolic model is easier to manage.

The geometric and symbolic location models have different overheads and levels of precision in representing location information. The appropriate location models to be adopted depends on applications. In this paper, we only consider the geometric location model.

2.4 Window Query

Due to the mobility of sensor nodes, querying the physical world based on IP addresses or IDs of the sensor nodes is not practical. For many applications of sensor networks which need to extract data from a specific geographical area, spatial queries such as window query and nearest neighbor search are essential. In this paper, we focus on window queries.

Window query enables users to retrieve all the data falls within the *query window*, a 2- to 3-dimensional area of interest defined by users. For example, consider a sensor network for an air pollution test, in which all sensors are scattered in the air and transported by the wind. Possible queries are: "What is the *average* pollution index value in a 10-meter space surrounding me?" or "Tell me if the *maximum* air pollution index value in Region X is over α?" In the first query, the query originates from inside the query window, but the latter one is issued from outside the window. In addition, in a vehicle network where sensors are carried by cars. A user may decide to change her driving route dynamically by issuing a query like "How many cars are waiting at the entrance of George Washington Bridge?" As seen in the above examples, practical window queries usually are coupled with aggregation functions, such as *AVG, SUM, MAX*, etc. Thus, aggregation is an important operation to be carried out by the sensor networks. Aggregation algorithms are important not only to provide computational support for those functions but also to reduce the number of messages and energy consumption in the network. How to efficiently aggregate and compute the functions in network is an actively pursued research topic in sensor database. We do not provide specific algorithms for aggregation functions, but focus on issues and strategies in enabling aggregation operation.

2.5 Performance Requirements

In order to assess the various enabling techniques for processing window queries in HDSNs, evaluation criterias need to be considered. In the following, we discuss some performance requirements:

- *Energy efficiency*. Sensor nodes are driven by extremely frugal battery resource, which necessitates the network design and operation be done in an energy-efficient manner. In order to maximize the lifetime of sensor networks, the system needs a suite of aggressive energy optimization techniques, ensuring that energy awareness is incorporated not only into individual sensor node but also into groups of cooperating nodes and the entire sensor network. Based on this remark, our work studies message routing, sensor cooperations, data flow diffusion and aggregation by taking energy efficiency into consideration. These concepts are not simply juxtaposed, but fitting into each other and justify an integrative research topic.
- *Total message volume*: Recent studies show that transmitting and receiving messages dominate the energy consumption on sensor nodes [19, 23]. Therefore, controlling the total message volume has a significant effect on reducing the energy consumption (in addition to the traffic) of the network. Furthermore, it also reflects the effectiveness of the aggregation and filtering of sensor readings. We expect that aggregation and filtering inside the network can reduce the total message volume tremendously.
- *Access latency*: This metric, indicating the freshness of query results, is measured as the average time between the moment a query is issued and the moment the query result is delivered back to the user. In addition to the lifetime of the sensor networks, access latency is important to the most of applications, especially the ones with critical time constraints. Usually there are tradeoffs between energy consumption and access latency.
- *Result accuracy and precision*: The other performance factors trading off with energy consumption and access latency are result accuracy and precision. High results accuracy and precision requires powerful sensing ability, high sampling rate, localized cooperation among sensor nodes, and larger packet size for transmissions. Approximate results with less precision may sometimes be acceptable by the applications. Network should achieve as high accuracy and precision of query result as other constraints allow.
- Query success rate: Query success rate is the ratio of the number of successfully completed queries against the total number of query issued by applications. This criteria shows how effective the employed query processing algorithms and network protocols are.

3. RESEARCH ISSUES

Although there exist some studies on various related issues of processing window query in highly dynamic sensor networks, they only address some

partial aspects of the problems. To the best of our knowledge, this paper presents the first effort to provide a complete suite of solutions/strategies to processing window query in HDSNs. In the following, we investigate the issues by considering the following query execution plan:

1. **Routing a query toward the area specified by its query window.** Once a user (or an application) issues a window query, the first question that needs to be answered is how to bring the query to the targeted area in order to retrieve data from sensor nodes located there. There exist many routing protocols based on state information of the network topology or the neighborhood to a routing node. However, the mobility of sensor nodes in HDSNs makes those protocols infeasible. In HDSNs, the state information changes so frequently that maintaining state consistency represents a major problem. It is very difficult (if not impossible) to obtain a network-wide state in order to route a query efficiently. Thus, *stateless* strategies need to be devised. Here we exploit the location-awareness of sensor nodes to address the need of stateless routing.

   An intuitive stateless routing strategy is *flooding* the network. Since each sensor node is aware of its own location, it can easily decide whether itself is within the query window or not. If a sensor node receives a query and finds itself located within the specified query window, it may return its sensed data back to the sender for processing while re-broadcasting the query to its neighbors. Flooding does not require the sensor nodes to have knowledge of their neighbors and the network in order to route a query to targeted sensor nodes, so it meets the constraints of HDSNs very well. However, all the drawbacks of flooding such as implosion, overlap and resource inefficiency are inherited. In addition, data is very difficult to aggregate by flooding.

   Considering the spatial nature of window queries and the location-awareness of sensor nodes, a class of protocols, called *geo-routing protocols*, that make routing decisions based on locations of sensor nodes and their distances to the destination looks promising. However, most of the existing geo-routing protocols require some knowledge of neighbors' locations to the sensor nodes in order to make a routing decision. In this paper, we propose a stateless geo-routing protocol, called *spatial query routing (SQR)*, which takes the strength of geo-routing protocols and employs various heuristics to fine tune the query routing decisions. Based on SQR, a window query is routed towards the area specified by query window based on sensor nodes' locations and energy awareness, without any state

information of neighbors or network topology.

2. **Propagating the query to sensor nodes located within the query window.** Once a query arrives in one of the sensor nodes located in the area specified by the query window, the sensor node may decide whether to start the *query propagation* mode right there or pass the duty to a more suitable sensor node (e.g., send the query to a node located at the center of the window). An algorithm for query propagation should try to satisfy the following two requirements: (1) cover all the sensor nodes located in the window; and (2) terminate query propagation when all the nodes received the query. A strict enforcement of requirement (1) can ensure that no sensor node misses the query. Any miss may lead to an inaccurate query result. However, this requirement is sometimes difficult to satisfy due to the dynamic nature of the sensor networks considered here. Thus, this requirement can be weaken, based on various specifications, to accept an approximated answer or an answer with less precision. Enforcing requirement (2) is critical because the query propagation process should stop once all the sensor nodes in the window receive the query.

   Conventional flooding algorithms can be modified to satisfy the above two requirements. Each sensor node maintain a query cache, which records all the queries it receives. When a sensor node receives a query, it first checks its query cache to see if there is a matching query. If yes, the query will be simply dropped; otherwise, the query is retransmitted to all its neighbors. In this way, query propagation terminates when all the sensor nodes inside the query window have the query in their caches. While the query cache can terminate the query propagation process, overhead inherited from flooding still exists. Furthermore, during the query propagation, sensor nodes may be still in move. Should the new nodes join the query processing? Should the nodes leave the window quit the query? The semantics and implied operations of queries need to be clearly defined.

3. **Collecting and aggregating the data in the query window.** As we pointed out earlier, aggregation is an important operation to be supported in sensor networks for computation of aggregation functions and for reducing the number of message transmissions and energy consumptions in the networks. Thus, instead of having all the sensor nodes located inside a query window send back their readings to the user for further processing, it is more efficient to process the data in network and only deliver the result back. To process

sensor readings based on certain aggregation functions and filtering predicates, the common wisdom is to assign a sensor node located inside the query window as an *aggregation leader*, who collects and processes the readings (or partially computed results) from other nodes. This approach may work for a static network. However, in our scenario, sensor nodes may move constantly so a fixed or static leader may not exist. Therefore, how to locate the leader in order to process the sensor readings locally and correctly is a challenge. In this paper, we introduce a concept of *leading region* to accommodate the mobility of aggregation leaders. Based on spatial space-division, we propose a solution, called *spatial propagation and aggregation* (SPA), for query propagation and data aggregation.

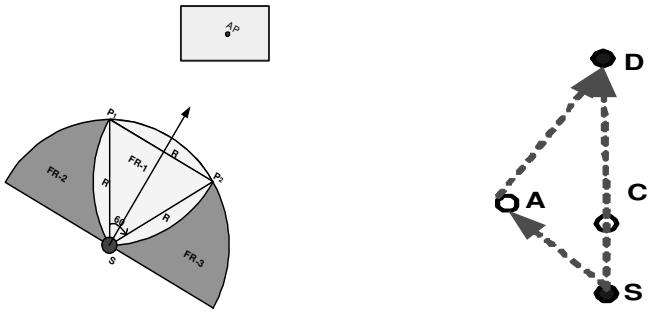
4. **Returning the query result back to the user.** After the query is processed, the result need to be delivered back to the user. Due to the user mobility, delivering the query result back to the user is not trivial. One intuitive approach is to route the result message based on sensor ID. However, in a highly dynamic sensor network, an ID-based routing implies flooding and thus imposes expensive energy and communication overheads. In this paper, we combine the geo-routing and a message forwarding strategy to solve the problem.

4. PROPOSED SOLUTIONS

In this section, we present several innovative solutions that we proposed to address the problems discussed in the previous section. We first describe *SQR*, a stateless spatial query routing method to route a window query towards the area specified by its query window. Then, we present *SPA*, an spatial space-division based approach for query propagation and sensor data aggregation within the query window. Finally, we discuss our solution for returning the query result to a user with mobility.

4.1 Spatial Query Routing

In HDSNs, it is difficult for a *sender*, the sensor node which currently holds a query message, to make query routing decisions without even knowing whether there exists a neighbor. Thus, an idea is to let the potential *query forwarders*, the sensor nodes reachable from the sender, decide whether they would voluntarily forward the query message based on their own state information, such as the distances from the sender and query window, their remaining energy levels, moving directions, speeds, etc. This approach is similar to the implicit geographical forwarding (IGF) protocol proposed in [16]. To facilitate the potential volunteers in making timely and proper decisions, the sender provides information such as



(a) Forwarding regions (b) Two paths from S to D

Figure 1: Spatial query routing.

its own location, the query window (specified by two points), the size of message, and other auxiliary information to prioritize the volunteer query forwarders. SQR consists of two primary tasks: 1) determining a volunteer to serve as the query router; and 2) setting up the next-hop query router based on *overhearing*. The goal of the second task is to reduce forwarding delays.

4.1.1 Volunteer Forwarders

To simplify the presentation, we use Figure 1 to depict a snapshot of the spatial query routing. A sender S, looking for a query forwarder, will broadcast messages to a space of radio range R. The routing of a query message is directed by aiming at a point in the query window, called *Anchor Point* (AP), determined by the application. In Figure 1, the AP is set to be the center of the query window. Here we assume that all the communications are bidirectional.

Once a sensor node receives a query and becomes the sender, it first decides its *forwarding region (FR)* based on the AP and its current position. The forwarding region is the upper part of the circle which is vertical to the line between AP and the sender. The FR is further divided by the sender into three parts:

- **FR-1** is the area with vertices S, P_1 and P_2, and surrounded by three curves. The curve connecting any two vertices is the partial circumstance of the circle centered at the remaining vertex. For example, the curve between P_1 and S is on the circle with center P_2. Therefore, any sensor nodes located inside FR-1 can hear each others' communications with the sender.
- **FR-2 and FR-3** are the two regions inside the FR, but which fall outside of FR-1. In other words, sensor nodes in these regions can communicate with the sender S, but are not necessarily aware of

on-going communications between sender and other sensor nodes in FR. FR-2 and FR-3 are separated by FR-1 (shown as the dark area in Figure 1(a)). Here we number the forward regions based on their forwarding priorities (as explained below).

There are many schemes to assign forwarding priorities to the regions. Here, the sender calculates three priority levels based on the distances of the forwarding regions to the query window. As illustrated in the figure, FR-1 has a higher priority than FR-2 which in turn has a higher priority than FR-3. To find the next query forwarder, the sender broadcasts a *Forwarder_Request* message to all its neighbors. The message contains the current location of the sender, query window, location of AP, and three timer (i.e., $Response\_timer_i$, where $1 \leq i \leq 3$) for the three FRs described above. Response_timer_i specifies the allocated period of time sensor nodes located in FR-i should respond to the sender. The responding priorities of sensor nodes in the same FR are determined by parameters such as its energy level, distance to sender and destination, etc.

Once receiving the message, a potential forwarder checks whether itself is located inside a FR. If not, the sensor node simply drops the message. Otherwise, based on which FR it is located within and the parameters considered below, the node computes and holds itself for a certain period of *holding time*. During the holding time, if the node does not hear from other neighbor nodes or the sender, it sends an *ACK_Forwarder* message back to the sender after the timer has expired; otherwise, it drops the message and cancels the holding timer. A node N inside FR may use some heuristics based on the following parameters to determine the holding time:

- **Remaining energy on the node** N. It aims to balance the energy consumption in the network. The node with higher energy remaining has a shorter holding time, thus suppresses the acknowledgements from other nodes in the same FR with less energy resources.
- **The distance between** S **and** N. The longer the distance between S and N, the shorter the holding time. The metric tries to reduce the number of hops between the source and the destination by forwarding the message as far away from S as possible. However to calculate the distance, S has to attache its location with the message. Moreover, using this metric may cause a longer path from the source to the destination. For example in Figure 1(b), S and D represent the source and the destination respectively. There are two possible paths from S to D: either $S \rightarrow C \rightarrow D$ or $S \rightarrow A \rightarrow D$. Based on this metric, the packet will follow the path of $S \rightarrow A \rightarrow D$.

Obviously it is not the best path from S to D, because longer transmission distance costs more energy.

- **The distance between N and the query window**. To overcome the side effect in the previous metric, the nodes can also take account into the distance between itself and the query window[1]. The N who has longer distance from the distance has longer timer.
- **Forwarding regions**. The sensor nodes located in FR-1 have a higher priority than those located in FR-2 and FR-3 to serve as a forwarder. The sensor nodes in FR-1 have to respond to the sender before $Response\_timer_1$ has expired. The sensor nodes in FR-2 will need to respond after $Response\_timer_1$ and before $Response\_timer_2$ has expired. The sensor nodes in FR-3 follow the same rule. Thus, nodes in FR-1 have shorter holding timers than the ones in FR-2, which have shorter timer than the ones in FR-3.

The situation where the the sender does not receive any *Ack_Forwarder* message from any of FRs implies that there is no node in FRs of the sender or that there exist some nodes there but none of them are willing to serve as a forwarder. This well-known *forwarding hole problem* can be resolved by existing solutions [10] or by re-try after waiting for a short period of time (since the network is dynamic).

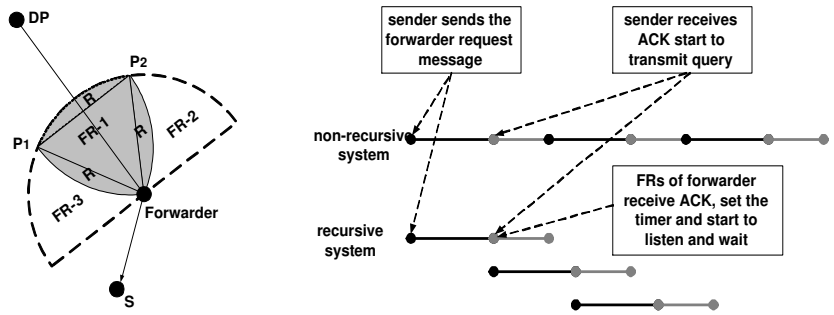
4.1.2 Pipelined Forwarding

In the forwarder volunteering process described above, the query forwarder has to wait for quite a while (i.e., after sending an *ACK_Forwarder* to the sender and receiving the query message from the sender) before it can look for the next forwarder. In this section, we introduce a pipelined forwarding strategy based on overhearing to reduce forwarding delay.

When a forwarder acknowledges the sender by sending an *ACK_Forwarder* message, the nodes inside forwarder's FRs also can overhear the message. To speed up the query forwarding process, we propose to have a potential forwarder to attach query forwarding information (which was given in *Forwarder_Request* message) in the *ACK_Forrwarder* message. Thus, the *ACK_Forrwarder* message is not only serving as the acknowledgement to the sender but also used to find the next forwarder.

For example, in Figure 2(a), when S hears an ACK from the forwarder, the sensor nodes in FRs circled by the dotted line can also hear the ACK, which contains enough information for those sensor nodes to decide whether to volunteer as the next forwarder. Figure 2(b) shows the timeline for three transmissions. Here is a simple analysis of the idea (assuming

[1]Depending on derived heuristics, the distance can be between N and the center, the nearest points, or AP of the window.



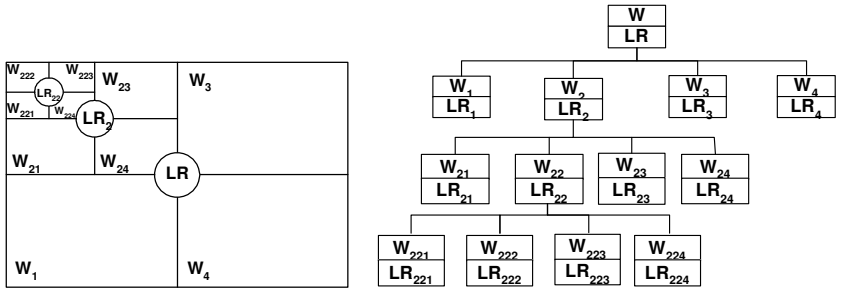
(a) Overhearing zone (b) Timeline for pipelined forwarding

Figure 2: Pipelined forwarding.

no conflicts happen). If the average *Response_Timer* is RT seconds, the average query transmission time is QT seconds, and the query message is forwarded M times before arriving the DP, the non-pipelined system takes $M \times (RT + QT)$ seconds for query forwarding, but the pipelining system only needs $M \times (RT + QT) - (M - 1) \times QT = M \times RT + QT$, and saved $(M - 1) \times QT$ seconds. We feel this idea is feasible and we are currently developing more detailed analysis to validate it.

4.2 Spatial Propagation and Aggregation

HDSNs bring major challenges to query propagation and data aggregation. Due to the mobility of sensor nodes and frequently changing network topology, the static aggregation leader and fixed infrastructure that is based on existing query propagation and data collection algorithms may not exist [14, 25, 28]. In this section, we propose a query propagation and data collection algorithm, called *spatial propagation and aggregation* (SPA), based on spatial space division and the concept of *leading regions* (LR), which are designated regions for dispatching query and processing aggregation. One of the sensor nodes in the leading region will serve as a *propagation and aggregation leader* (PAL) to decide how to propagate a query to space-divided subareas and to collect data from those subareas for aggregation. The size and location of a leading region can be present or adapted during run-time. The PAL of a leading region can be determined by volunteering (based on various constraints of the sensor nodes), voting (based on group decision), or designating (e.g., the first node receives the query). In addition, the PAL can adjust its LR before it proceeds to propagate queries. The size of LR can be determined by the mobility of PAL and density of nodes in the area. The main difference between the leading area here and the leader in static sensor networks is that a leading area addresses a fixed geographical area instead of some



(a) Leading region (b) Hierarchy for query spreading

Figure 3: Spatial propagation and aggregation.

specific nodes which are dynamic in HDSNs.

Based on the ideas discussed above, we use Figure 3 to further illustrate our SPA algorithm. While the leading areas can be of any shape, we represented them as circles to distinguish from the sub-windows. Once a query is received by a sensor node in the query window, the sensor node can decide to 1) serve as the PAL for the window by specifying an LR and start the SPA algorithm; or 2) forward the query to a temporary LR (e.g., center of the window) and allow more qualified nodes there to volunteer. Assume that a sensor node in the temporary LR decides to serve as the PAL, it will specify its LR and then start the SPA algorithm.

The SPA algorithm we proposed is recursive. Once the PAL in charge of the whole window and its LR are determined, the query window W is divided into four sub-windows, namely W_1, W_2, W_3 and W_4. For each sub-window W_i where i is the subscript of the sub-window, a circle area in the middle is temporarily assigned as the leading region, denoted as LR_i. The query will be propagated to the four leading regions by using SQR protocol described earlier. After a query arrives at the temporary leading region in the sub-window, a PAL in charge of the sub-window is determined and its refined LR are obtained. Thus, each sub-window (W_i) is further divided into even smaller windows, i.e., W_{i1}, W_{i2}, W_{i3} and W_{i4}. The recursive splitting and forwarding procedure is repeated until a stop condition is satisfied, which will be discussed later in this section. Once the splitting and forwarding process stops, sensor nodes report their readings back to their leading region where the PAL will collect and aggregate the data. Once the PAL decides that there are no more reports from the area it leads, it sends the aggregated data to the leading region at an immediate higher level. This aggregation process is repeated until the PAL for the whole query window receives the aggregation result from all of its children LRs. However, there are still several questions need to be answered in the above seemingly simple recursive algorithm:

1. **How large should the leading region be?** In SPA, the leading region is set by the PAL based on its mobility and the network density, so that there is always at least one sensor node in the region. Further analysis is needed to obtain the optimal leading region. To address the rare scenario that there is no sensor in the leading region, one possible solution is to extend the routing protocol such that the data may be sent to the upper-level leading areas.
2. **How do we deal with the scenario that the PAL moves out of the leading region before the aggregation is completed?** Once the PAL realizes that it is close to the boundary of leading region and probably will move out of the region, it floods the leading region to find a new PAL. When a new PAL is found, the old PAL hands off the partially completed aggregation result and other needed information (e.g., the higher level leading region, information about the lower level region) to the new PAL. As such, the data collection and aggregation process is not interrupted.
3. **What is the stop condition for recursive splitting and forwarding?** Many heuristics can be used. For example, the size of sub-windows or the ratio of window size versus LR size. Once a PAL stops window splitting and query propagation, it floods the query inside the sub-window that it is in charge and waits for the data from the sensor nodes inside its window. Since flooding is constrained in a very small region, duplicated transmissions are reduced.

4.3 Returning the Query Result Back to the (Mobile) User

Once the PAL at the highest level obtains the query result, it will return the result back to the user (i.e., the query issuer). Due to the unlimited mobility, a user may move while the query is processed. Therefore the location where the query was issued may not be the exact location where the result should be delivered.

To address this problem, an *issuer region*, which defines the region where the user may stay in (while moving) during query processing, will be included as part of the query routed towards the query window. Thus, instead of routing the query result based on the user's identifier or exact location, the stateless SQR protocol (as described in Section 4.1) is used to send the result back to the issuer region. Once the query result reaches the issuer region, it is flooded to the whole region.

Similar to decide a leading region in the SPA algorithm, a user should specify a precise area that will accommodate his/her future movement. However, in the rare occasion that the user moves out of the issuer region, it will specify a new region which may or may not overlap with the original

region, called the *extended issuer region* (EIR), and pass this information to a sensor node, called the *forwarding agent* (FA), located in the old region. If the FA has to move out of the old issuer region, it will find a substitute to serve the role of forwarding agent and pass the information of EIR to the new FA. This forwarding mechanism will be established if the user has to move out of the new EIRs too. Thus, the query result may go across several forwarding agents until reaching the user.

5. RELATED WORK

To the best of our knowledge, window query process in highly dynamic sensor networks has not yet been studied in the sensor network and database research community. However, our work has been informed and influenced by a number of research efforts.

Energy-efficient data dissemination is among the first set of related research issues being addressed. SPIN is one of the early works that is designed to address the deficiencies of classic flooding by negotiations and resource adaption [5, 12]. Directed Diffusion takes a data-centric naming approach to enable in-network data aggregation [9]. By employing initial low-rate data flooding and gradual reinforcement of better paths, directed diffusion accommodates a certain level of sensor nodes dynamics. TTDD proposed by Ye et.al targets a scalable and efficient data delivery to multiple mobile sinks in a large sensor network [27]. TTDD enables mobile sinks to continuously receive data on the move at the cost of building up a grid structure for each data source within the whole network. Instead of purely flooding data or a request, rumor routing algorithm proposed by Braginsky et al. is a logical compromise [2]. A source sends out"agents" which randomly walk in the sensor network to set up event paths. Queries also randomly walk in the sensor field until they meet an event path. Such previous work investigates energy-efficient data dissemination protocols in stationary or low-mobility sensor networks, since frequent movements of upstream nodes on the route may cause a new route discovery procedure or high route maintenance expense. In our proposal, sensor nodes make decisions to route a query without any state information of other nodes or networks, thus suitable for the sensor networks with unstable topology.

In addition, recent work has explored the routing algorithm for window query in static sensor networks [28]. Specifically GEAR showed how the geographical forwarding technique can help achieve energy efficiency for routing the query toward the window and spreading the query inside the window. Our ideas not only explore the query forwarding and dissemination in a stateless way, but also the data collection and aggregation and delivering the result back to the users in HDSN.

Some of the inspiration for our studies comes from [26], which enables the distributed and localized sensor operations to improve the scalability. Ye et.al proposed an original forwarding scheme for maintaining relatively constant working node density, thus prolonging the system lifetime.

Many of the energy-aware techniques developed for improving sensor network performance can be adopted by our study. For example LEACH [4] proposes a clustering based protocol that utilizes randomized rotation of local cluster heads to evenly distribute the energy load among the sensors in the network. Our proposal has the additional degree of freedom in being able to use application semantics to achieve further efficiency.

Our work borrows heavily from the literature on ad hoc routing. Specifically, it is close related to the geographical routing algorithm proposed in [10] where each sensor node greedily forwards the packet based on the knowledge of its neighbors. As a state-based algorithm, it suffers expensive upkeep of neighbor changes due to the system dynamics. The LAR, in its attempt to constrain the flooding into smaller possible region instead of the whole network, is another closely related work [11]. However the effectiveness of the estimation for requested zone in the LAR is restricted by the destination's previous known location and its know mobility pattern.

Implicit geographical forwarding (IGF) proposed by B.M. Blum et. al [16] is probably the most relevant work to the SQR discussed in the paper. IGF designs a state-free routing algorithm for sensor networks, by assuming high node density and location awareness in the networks. In IGF, sensor nodes make forwarding decisions dynamically based on their current conditions (i.e., distance to the destination and remaining energy). However, this work has focused on adapting the underlying MAC layer to avoid the communication collisions. Moreover, IGF considers only the sensor nodes residing in a small region (which is part of the FR-1 in SQR) for forwarding and relies on shifting the forwarding area to handle the situation when there are no sensor nodes in the forwarding zone. Our SQR protocol tries a much larger area for forwarding and sets up different forwarding zones. The issue we are focused on is how to set up the minimal zone timers while reducing collisions within a zone and to ensure no communication interference between the zones. Specifically, SQR defines much wider forwarding region (which consists of FR-1, FR-2 and FR-3) and assigns them different forwarding priorities. Another primary difference between IGF and SQR is that pipelining is employed by SQR to reduce the forwarding latency. Therefore, we are interested in exploiting (via SQR) some of the related issues considered in [16] but in a more sophisticated context.

Our work is influenced by the data management researches in sensor

networks as well. In Moving Objects Database (MOD), a base station (gateway) outside the network collects the sensor readings and answers user queries [22, 24]. However the centralized approach incurs heavy transmission overhead and consumes extensive energy. Our work focuses on extracting and aggregating the data locally inside the network, thereby reducing the duplicate and unnecessary transmissions. In both TinyDB and Cougar projects, the query is executed directly on the sensor nodes instead of on the gateway. Therefore, the sensor readings are only extracted out when a query is inserted into the network. TinyDB develops the techniques for query result aggregation and filtering on site by building up a semantic tree [13, 14]. Cougar project studies the query execution plan and query optimization in the sensor networks [25].

6. CONCLUSION

Motivated by future sensor network applications, we studied the problem of window query execution in highly dynamic sensor networks, where the network topology changes frequently. The proposed suite of protocols forwards the query toward the queried window based on the location of the sensor nodes; propagates the query inside the query window recursively and ensures the coverage of the window; aggregates the sensor readings at certain geographical region before delivering it back (which adapts to the mobility of sensor nodes and reduces the amount of transmissions); guarantees that the query issuer receives the result even if he is in movement. Our protocols explore the static property of geographical location to accommodate the mobility of both sensor nodes and users.

Some issues remain to be further exploited such as the heuristics for forwarder selection, zone timer settings, and the size of the leading regions. Other future work includes developing simulations and implement prototypes to validate our proposals.

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